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The anomalous pressure drop behaviour of ice slurries flowing through constrictions

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Abstract

The effective 'viscosity' for ice slurry containing more than say 30 to 40% ice fraction is many orders of magnitude higher than that for water. However, this work suggests that such slurries, when flowing through constrictions, can incur lower pressure drops than water flowing at the same rate through the same topology. This paradoxical finding is explored, studied and reported in this paper. It is thought that this reduction in pressure drop is the result of ice particles inhibiting the onset of turbulence in the ice slurry. Other researchers have previously observed this phenomenon in slurries of lower ice fractions. It is also suggested that the relatively low pressure drops observed for high ice fractions may be due to complex heat transfer and phase change phenomena, which are likely to occur at the ice-wall interface.

Keywords: Ice slurry; pressure drop; ice pigging; turbulence inhibition; drag reduction.

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1. Introduction

Ice slurries are used extensively for cooling although their use has spread to other application areas, some of which are given by Davies (2005) and by Bellas and Tassou (2005). Ice slurries exploit the latent heat of the ice, making them more efficient heat carriers than single-phase fluids. Their large thermal capacity and lower operating temperatures allow larger temperature differences to be maintained,

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providing desirable heat sink characteristics. Studies into the behaviour of ice slurries have tended to concentrate on the heat transfer characteristics of low ice fraction slurries. Work carried out to measure the pressure drops of flowing ice slurries has investigated the flow behaviour of ice slurries with ice fractions of less than about 45% where:

$$\text{Ice fraction} = \phi_s = \text{Vol.}_{\text{solids}} / \text{Vol.}_{\text{slurry}} \tag{1}$$

Kaushal et al. (2005) have worked on slurries with volumetric solid fractions of up to 50%. However, this and the earlier work of Kaushal et al. (2002) have tended to focus on observations of the flow regime and concentration profile of slurries with a significantly denser solid phase. Kaushal et al. (2005) observed interesting pressure drop behaviour, which were attributable to the different flow regimes that occur with changing solid fraction, flow velocity and particle diameter. In general, Kaushal et al. (2002) found that thicker slurries of smaller particles flowing at higher velocity are more homogeneous. This is also supported by the work done by Kitanovski and Poredoš (2002) on the particle distribution in flowing ice slurry.

The behaviour of ice slurries with ice fractions over 45% is less well known and the data and opinions of authors are divergent (Frei and Egolf (2000); Ayel et al. (2003); Cheng and Law (2003)). The most commonly used model for the viscosity of ice slurries was formulated by Thomas (1965) but this equation is seen to over-predict the viscosity of slurries with an ice fraction of more than 15% (Hansen et al. (2000)). This paper details work that has been carried out to investigate the pressure drops in flowing ice slurries with ice fractions greater than 40%.

2. Background

The University of Bristol has been carrying out work into the development of a novel system of clearing product pipelines. The concept, patented by Quarini (2001), involves using thick ice slurry to form a "pig". The slurry ice has properties that are ideally suited to this application: it presents a 'solid' piston-like profile in constant diameter ducts and yet deforms like a thick fluid if the topology demands it. Hence slurry ice can be used to 'separate' one specific food product from another in the same pipe whilst they are being pumped (Quarini (2002)). Ice pigs have been used in many applications in the food industry (Quarini (2002)) and have been found to be 'pumpable' even with very high ice fractions (Quarini (2003)). Visual observations of the ice pig travelling through glass pipes provide evidence of its self-healing properties and its ability to remain relatively stiff, even after melting has occurred. Shire et al.

(2005) have proposed a simple theoretical model, which is in qualitative agreement with the experimental results.

3. Experimental facility

3.1. Slurry ice formation

The ice slurries used in all the tests were generated using a Ziegra ice machine. The ice fraction is controlled by adjusting the residence time of the brine/slurry in the freezer section of the machine. The crystals produced are of a finger-like, prolate form such as ellipsoids (Hansen et al. (2002)) or spherocylinders (Sari et al. (2000)). Typically a crystal may be 20-50μm wide and perhaps 100-200μm long. These fine crystals give the slurry ice a paste-like feel and soft texture.

3.2. Ice fraction measurement

Ice fraction was estimated using a coffee press (mesh plunger) to separate the liquid and solid fractions of slurry samples. The technique has been found to produce quick and repeatable (to within 3%) results for this type of ice slurry. However, measuring ice fraction is notoriously difficult and there is no universally accepted method for doing so (Hansen et al. (2002)). Recent work by Ayel et al. (2005) provides a method for direct measurement of freezing point and solution concentration from the sub-cooling of glycol solutions, which would allow for more accurate use of temperature: ice concentration relationships. The work of Lottin et al. (2004) also considers the enthalpy and heat capacity of glycol ice slurries to allow optimisation of transport properties and definition of an operational envelope. Further literature and discussion of ice fraction measurement are given by Evans et al. (2007).

3.3. Experimental flow sections

The experimental flow sections were constructed using sections of borosilicate glassware with an internal diameter of 25mm. The use of these glass pipe sections allows the flow to be observed and also allows different topologies to be set up simply by connecting different pipe sections to the flow test section. Two different topologies were investigated: a 1m long straight pipe and a similar section containing a 12.7mm diameter orifice plate at its mid-point. Flush fitting gaskets and tapping plates for transducers were used to connect the sections of pipe work. This was done to ensure that the flow and pressure readings were not disturbed by discontinuities in the pipe wall.

3.4. Instrumentation

The pressure drop across each section was measured using piezo-resistive gauge pressure transducers. Before each test the transducers were simultaneously zeroed and then calibrated for the range of pressures experienced during the tests. After calibration the transducers were checked under dynamic pressure loading with a no-flow condition to ensure that their responses were equal.

Calibration of the measuring system (transducers and amplifiers) demonstrated that the system gave reproducible results with no hysteresis and an accuracy of ±100Pa. This gave an accuracy of better than ±5% for the range of pressure drops experienced by the ice slurries. The calculated pressure drop across the test section was found by averaging data for the entire period of each flow setting.

The flow rate of each experiment was calculated by measuring how long it took for 4 litres of ice to flow through the test section. During each experiment the slurry ice was directed into an agitated measuring vessel. This measurement was repeated twice and the average of the three times recorded in order to calculate the flow rate. It was estimated that this technique was accurate to within ±5%.

4. Experimental procedure

Approximately 80 litres of slurry ice was produced from a brine solution of 4.76% NaCl by weight and loaded into the tank on the experimental rig (see Fig. 1). This relatively large volume of ice allowed the ice fraction to be maintained during the course of each experiment. The tank has a cylindrical shape and the outlet is positioned in the bottom at the sidewall of the tank. The slurry ice in the tank was agitated using a paddle mixer during all experiments and whilst the ice slurry was being pumped from the tank in order to achieve an homogeneous slurry.

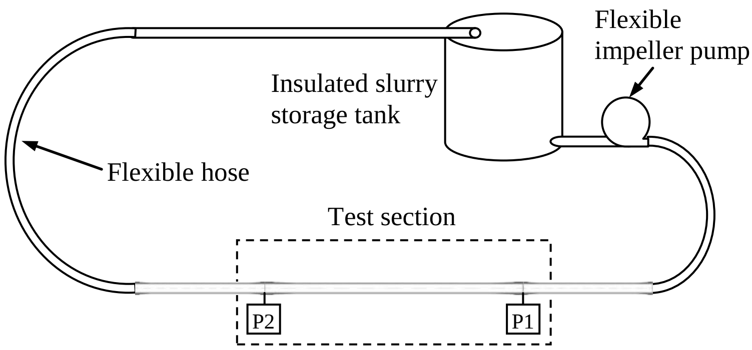


Fig. 1. Experimental set-up.

Before each test was carried out, ice was circulated through the test section for several minutes to reduce the temperature of the components and ensure quasi-static conditions for the experiments. The ice fraction was then measured and recorded.

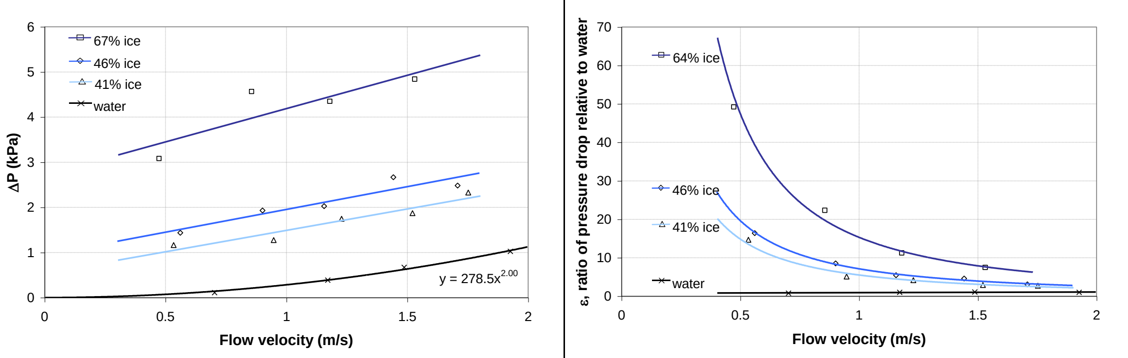
The pump was set to a low speed setting and the ice slurry was circulated through the test section and measurements taken of flow velocity and pressure drop. After approximately 1 minute, the pumping speed was increased and readings taken for the new flow rate and pressure drop data. This procedure was repeated for several flow speed settings in order to obtain data for pressure drops over a range of flow speeds. At the end of the tests, the ice fraction of the slurry was again checked using the coffee press in order to establish any change in ice fraction.

The tests were repeated for slurries with different ice fractions, again logging data for the pressure drops over a range of flow rates.

5. Results

5.1. Straight horizontal pipe

The pressure drop across the test section was plotted against the flow rate for each ice fraction (Figure 2a). Trend-lines have been added to the plots to give a better indication of the general behaviour of the slurries flowing through the test sections.



a). Pressure drops for 1m straight section.

b). Pressure drop ratios for 1m straight section.

Fig. 2. Flow through a straight 1m long pipe.

The plot in Figure 2a for the straight pipe shows that the pressure drop increases with increasing flow rate and also with increasing ice fraction. The pressure drop has been modelled as a function of the flow rate by the superimposed trend-lines.

The pressure drop for water has been modelled using a power relationship in the form of equation 2 below. For the straight section, the best-fit value for b was found to be 2, suggesting a turbulent flow regime, which is expected for or U>0.16m/s (Re>4000).

$$\Delta P = a.U^{b} \tag{2}$$

where ΔP is the pressure drop, U is the flow velocity and a and b are fitting parameters (constants).

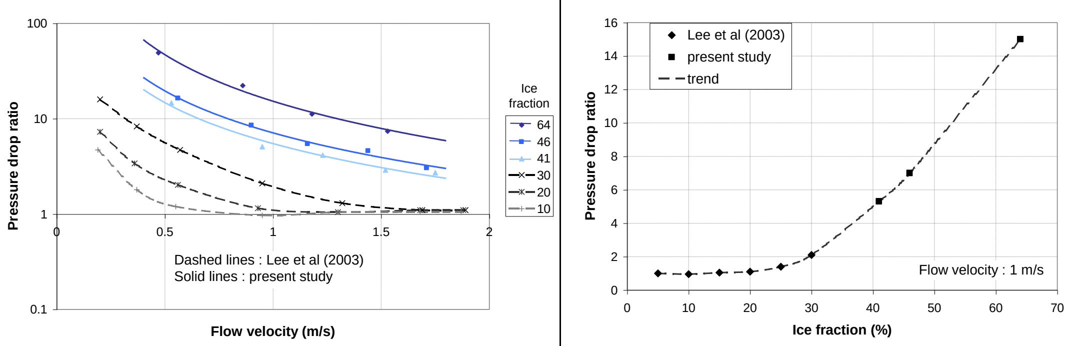
The pressure drop across each section for flowing ice slurry has been modelled using a linear fit of the form of equation 3 below.

$$\Delta P = a.U+b \tag{3}$$

The choice of fit depends upon the model of viscosity being taken to represent the behaviour of the ice. Ice slurries of low ice fraction are thought to behave like Newtonian fluids but slurries of higher ice fraction exhibit Bingham behaviour (Hansen et al. (2000)). These thick slurries exhibit a critical yield stress, which is not a fundamental fluid property but dependent upon the means of measurement (Nguyen and Boger (1983)). The straight lines fitted here comply with a Bingham model for the viscosity of the ice slurry. A power law fit to the data for the ice slurries would result in a power of less than 1, corresponding to a shear thinning fluid. This type of fit would suppose an Ostwald type model for the viscosity and would not model the yield stress of the ice slurry. Possibly better, would be to produce a fit based on the Herschel-Buckley model for viscosity, which includes both the power law relationship and a non-zero yield stress. The Herschel-Buckley model would help avoid the over-estimation of yield stress, which is a consequence of using the Bingham fluid model. The difficulty in producing extensive data sets, and resultant dearth of points upon which to base any fits, renders complex modelling pointless. Despite this, it is apparent that the pressure drop for ice slurries of high ice fraction is more dependent upon any critical yield stress.

The relative difference in pressure drop between flowing water and each of the flowing ice slurries is seen to be greatest at lower flow rates. As the flow rate increases, the difference in pressure drop is reduced; this is illustrated in Figure 2b above. The figure shows the ratio of pressure drop for each of the slurries to the pressure drop exhibited by water plotted against flow rate. The pressure drop ratio is calculated by taking the pressure drop measured for each of the ice slurries and dividing by the pressure drop exhibited by water at the same flow rate. The pressure drop for water is calculated for each flow rate from the fit given in Figure 2a (ie. $\Delta P_w=278.5U^2$). This equation represents the best fit to the experimental data for water flowing through the same relatively short length of pipe in the same experimental set-up.

Grandum and Nakagomi (1997); Snoek et al. (1995) and Inaba (2000) have made these same observations and the present results are in qualitative agreement with almost all of their findings. Of all the previous work, Lee et al. (2003) performed experiments on pipe sections most similar to those used in the present study. Lee's work focussed on ice slurry flow through pipes with an internal diameter of 24mm for slurries with an ice fraction of up to 30%. Some of their findings are presented in Figure 3 along with results from the work presented here.



a). Pressure drop ratios for 1m straight sections.

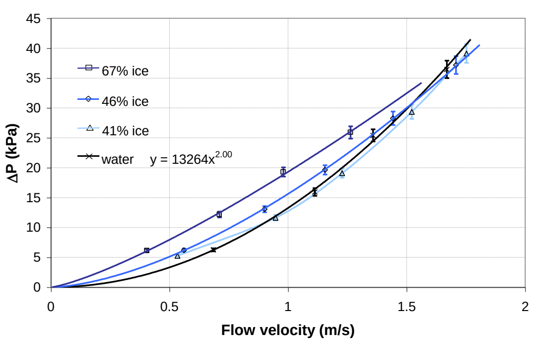
b). Pressure drop ratio vs ϕ for flow at 1m/s.

Fig. 3. Comparison of results for flow through a straight 1m long pipe.

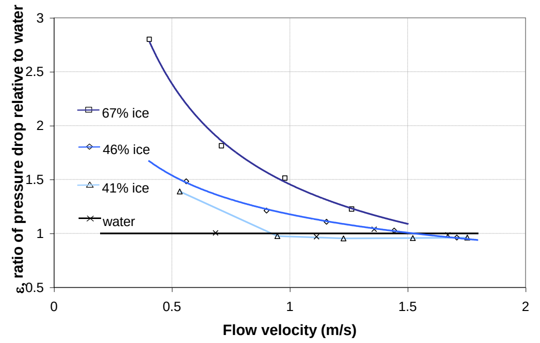
Figure 3a shows the same data as Figure 2b, combined with Lee's data for ice slurries of 10, 20 and 30% ice fraction. Figure 3b shows the pressure drop ratio data plotted against ice fraction for a flow velocity of 1m/s. It can be seen that the results presented here extend the work of Lee et al. (2003) to higher ice fractions. The data from this work closely follow the trends identified by Lee of rapid increase in pressure drop ratio for ice fractions above 20% and the tendency to unity at high flow rate.

5.2. Straight pipe with orifice

Figure 4a shows the pressure drop through the 1m straight section of pipe containing an orifice. The diameter of the orifice was half the diameter of the pipe, giving a 4:1 reduction in cross-sectional area. There was a much higher pressure drop across this test section; typically it was 5-6 times higher than for the straight test section. Again, the pressure drop has been modelled using an equation of the form of equation 2. As might be expected, for water $b \approx 2$ and $\Delta P \propto u^2$, which is a well known result for situations in which the hydrodynamic characteristics of a system are dominated by inertial losses.



a). Pressure drops for 1m orifice section.



b). Pressure drop ratios for 1m orifice section.

Fig. 4. Flow through a straight 1m long pipe containing an orifice at its midpoint.

The pressure drop increases with flow rate and b (in equation 2) is lower for higher ice fractions. The flow regime appears to be different here and the pressure drop is more dependent upon flow rate. The difference in pressure drop between the water and the ice slurries is less apparent and the pressure drop ratio is seen to be much lower than for the straight section (see Fig. 4b.). The trends observed for the straight pipe are also apparent here, with the pressure drop ratio higher for higher ice fractions and converging around unity for all ice fractions at high flow rates. In fact, at higher flow rates, the water required a slightly higher pressure differential to drive a given flow than the slurries with 40% ice content. This is contrary to most other researchers, who suggest that for a given pipe topology, $\Delta P_{slurry} \geq \Delta P_{water}$ for all ice fractions and flow rates.

6. Discussion

Thick (high ϕ) ice slurries tend to exhibit slightly lower pressure drop characteristics than might be expected by simply studying the models of viscosity. Ice slurries with high ice fraction are highly viscous fluids with viscosities several orders of magnitude greater than water. These thicker ice slurries tend to exhibit a homogeneous, plug flow even at low velocities (when slurries with a lower ice fraction exhibit heterogeneous, moving bed flow). This plug flow characteristic is made possible by a lubricating liquid layer that forms at the pipe wall, as proposed by Vand (1948).

This layer is primarily formed because of topological limitations that prevent ice crystals coming to within their own radius of the wall. However, almost all of the heat transfer to the ice slurry occurs through the wall of the pipe and this causes crystals near the wall to melt, further enhancing this effect. The effect is well known to rheologists studying slurries where it is termed ‘glide’ or ‘slip’ and hinders easy assessment of a slurry’s viscosity when using a rotational viscometer (Barnes (2000); Ayel et al. (2003)).

One might suppose, as Vand (1948) did, that if the ice crystals cannot exist over the entire cross section of the pipe then this might force more crystals into the centre of the pipe, where they would reach a higher ice fraction and make the slurry correspondingly more viscous. However, because of the presence of the lubricating liquid layer and the plug flow nature of the flow, the crystals are actually forced to travel through the pipe in the central core at a higher relative velocity (Maude and Whitmore (1956)). Hence, the residence time of the ice crystals is reduced and thus also the effective ice fraction of the slurry within the pipe. Higginbottom (1958) showed that this effect is most noticeable where the pipe diameter is small (relative to the size of suspended solids) and the lubricating liquid layer occupies a relatively large proportion of the flow area (eg. at the orifice). This relatively deep lubricating layer of liquid provides greater slip and further reduces the residence time of the ice crystals in the orifice. The combined glide effects and reduced residence time of ice crystals at the orifice lead to a reduction in the apparent solid fraction and effective viscosity of the slurry at the orifice.

a) 0s　b) 0.1s　c) 0.2s

Fig. 5. Passage of 60 % ice slurry through an orifice at a flow velocity of 0.4 m/s.

Figure 5 demonstrates the plug flow profile and laminar flow regime exhibited by these thick ice slurries. The slurry is flowing from right to left and is coloured white and red for visualisation purposes. Figure 5c shows that the profile remains undisturbed by the orifice plate.

It is believed that the ice crystals inhibit the development of turbulence in the ice slurries and that this could explain the reduction in pressure drop as compared to water. The ice crystals at the core of the pipe help to maintain a laminar flow, reducing inertial pressure losses. This is a characteristic of the ice slurries that has previously been observed by Quarini (2002). Knodel et al. (2000) and Liu et al. (1997) have observed a re-laminarization phenomenon but their studies considered ice slurries of less than 10% solids and with particle sizes greater than 1mm in constant diameter pipes.

The orifice plate causes a constriction, which increases the pressure upstream. This pressure is still relatively low in the fluid as a whole but locally the shear and impact induced pressure on some portions of some ice crystals may be much higher. As ice crystals impact upon the orifice plate, there may be very high pressure and shear forces generated locally where the tip of a crystal comes into contact with the wall. This localised high pressure will cause the crystal to melt where it contacts the pipe wall or orifice. This localised melting will lubricate the flow further, allowing the slurry to negotiate particularly tortuous topologies where other slurries may be expected to require especially high driving pressures or block the pipe entirely. As the pressure is released, the ice/water refreezes, returning the slurry to its original equilibrium and stiffening the slurry again when the flow path becomes easier.

7. Conclusions

The results of this work have shown that thick ice slurries (more than 40% solids) continue the trends in behaviour observed by other researchers for ice slurries with lower solid fraction. For constant diameter pipes, the pressure drop has been shown to increase both with ice fraction and mean flow rate. The pressure drop is seen to be more dependent upon a critical yield stress for ice slurries of higher ice fraction. The pressure drop ratio of ice slurries to water was less at higher flow rates.

The heat transfer and topological constraints present for ice slurry flows allow the slurry flow to remain well lubricated by a liquid layer at the wall. This liquid layer provides slip at the wall and results in the low pressure drop ratios that were recorded for the very thick slurries studied here.

Study of the ice flow through an orifice highlighted a previously unseen phenomenon. A slight pressure drop reduction was observed for ice slurries of over 40% solids when compared with the pressure drop for water at the same mean flow rate. This phenomenon had only been observed in ice slurries with ice fraction below about 10%. The drag reduction phenomenon is thought to result from the particles in the slurry preventing or reducing the development and effects of turbulence in the flow. This hypothesis is supported by observations made of the ice slurries flowing through orifice plates, where the ice crystals provide an inherent flow visualisation aid. These visualisation studies suggest that little or no stochastic mixing occurs within the ice slurry and a laminar flow regime is maintained.

There are also thought to be some other more localised effects resulting from heat and mass transfer at very localised regions of high pressure. The localised melting and refreezing of ice crystals at the orifice may also account for the very low pressure drop ratios exhibited by these thick slurries. This is a characteristic unique to slurries of a single material (ice slurries) in which the material can change state/phase.

References

Ayel, V., Lottin, O., Peerhossaini, H., 2003. Rheology, flow behaviour and heat transfer of ice slurries: a review of the state of the art. Int. J. Refrigeration 26, 95-107.

Ayel, V., Lottin, O., Popa, E., Peerhossaini, H., 2005. Using undercooling to measure the freezing points of aqueous solutions. Int. J. Thermal Sciences 44, 11-20.

Barnes, H.A., 2000. Measuring the viscosity of large-particle (and flocculated) suspensions – a note on the necessary gap size of rotational viscometers. J. Non-Newtonian Fluid Mechanics 94, 213-217.

Bellas, I. and Tassou, S.A., 2005. Present and future applications of ice slurries. Int. J. Refrigeration 28-1, 115-121.

Cheng, N-S., Law, A.W-K., 2003. Exponential formula for computing effective viscosity. Powder Technology 129, 156-160.

Davies, T.W., 2005. Slurry ice as a heat transfer fluid with a large number of application domains. Int. J. Refrigeration 28-1, 108-114.

Evans, T.S., Quarini, G.L., Shire, G.S.F., 2007. Investigation into the transportation and melting of thick ice slurries in pipes. Int. J. Refrigeration, ARTICLE IN PRESS, (doi:10.1016/j.ijrefrig.2007.06.008).

Frei, B., Egolf, P.W., 2000. Viscometry applied to the Bingham substance ice slurry. Proc. 2nd Workshop on Ice Slurries. IRR, 48-60.

Grandum, S., Nakagomi, K., 1997. Characteristics of ice slurry containing antifreeze protein for ice storage applications. J. Thermophys. Heat Transfer 11, 461-6.

Hansen, T.M., Kauffeld, M., Grosser, K., Zimmerman, R., 2000. Viscosity of ice slurry. Proc. 2nd Workshop on Ice Sslurries. IRR, 38-45.

Hansen, T.M., Radošević, M. and Kauffeld, M., 2002. Behaviour of ice slurry in thermal storage systems. ASHRAE research project RP 1166, Danish Technological Institute.

Higginbottom, G.H., Oliver, D.R., Ward, S.G., 1958. Studies of the viscosity of suspensions. British J. Applied Physics 9, 372-377.

Inaba, H., 2000. New challenge in advanced thermal energy transportation using functionally thermal fluids. Int. J. Thermal Science 39, 991-1003.

Kaushal, D.R. and Tomita, Y., 2002. Solids concentration profiles and pressure drop in pipeline flow of multisized particulate slurries. Int. J. Multiphase Flow 28, 1697-1717.

Kaushal, D.R., Sato, K., Toyota, T., Funatsu, K. and Tomita, Y., 2005. Effect of particle size distribution on pressure drop and concentration profile in pipeline flow of highly concentrated slurry. . Int. J. Multiphase Flow 31 (5), 663-671.

Kitanovski, A., Poredoš, A., 2002. Concentration distribution and viscosity of ice-slurry in heterogeneous flow. Int. J. Refrigeration 25, 827-835.

Knodel, B.D., France, D.M., Choi, U.S., Wambsganss, W.M., 2000. Heat transfer and pressure drop in ice-water slurries. Applied Thermal Engineering 20, 671-685.

Lee, D.W., Yoon, C.I., Yoon, E.S. and Joo, M.C., 2003. Experimental study on flow and pressure drop of ice slurry for various pipes. Proc. 5th Workshop on Ice Slurries, IRR, 22-29.

Liu, Y.H., Zhang, Z., Zhao, J., Chen, P., 1997. Experimental study on friction loss characteristics of pipes with ice slurry. Science et technique du froid. Air conditioning in rise buildings ’97 3, 9-12.

Lottin, O., Ayel, V., Peerhossaini, H., 2004. Ice slurries phase transition thermodynamics: relations for determining concentration-temperature domains of application. Int. J. Refrigeration 27, 520-528.

Maude, A.D., Whitmore R.L., 1956. The wall effect and the viscometry of suspensions. British. J. Applied Physics 7 (3), 98-102.

Nguyen, Q., Boger, D.V., 1983. Yield stress measurement for concentrated suspensions. J. Rheology 27, 321-349.

Quarini, G.L., 2001. Patent number WO0151224, GB2358229, AU2533001, EP1248689, Cleaning and separation in fluid flow conduits.

Quarini G.L., 2002. Ice-pigging to reduce and remove fouling and to achieve clean-in-place. Applied Thermal Engineering 22, 747–753.

Quarini, G.L., 2002. Send in the ice pig!. Food Science and Technology 16 (2), 46-50.

Quarini, G.L., 2003. Pigging with pumpable ice -update. Food Link News 45, 4.

Sari, O., Vuarnoz, D., Meili, F., Egolf, P.W., 2000. Visualisation of ice slurries and ice slurry flows. Proc. 2nd Workshop on Ice Slurries. IRR, 68-81.

Shire, S., Quarini, J. and Ayala, R.S.,2005. Experimental Investigation of the mixing behaviour of pumpable ice slurries and ice pigs in pipe flows. Proc. Inst'n Mech. Eng'rs, Part E, J. Process Mechanical Engineering 219, 301-309.

Snoek, C., Joanis, S., Gupta, R., 1995. Pressure drop characteristics of ice-water flows. Two Phases Flow Model Exp 1995, 655-63.

Thomas D.G.,1965. Transport characteristics of suspension. VIII. A note on the viscosity of Newtonian suspensions of uniform spherical particles. J. Colloid Science 20, 267-277.

Vand, V., 1948. Viscosity of solutions and suspensions. 1. Theory. J. Physical and Colloid Chemistry. 52 (2), 277-299.

Figure Captions

Fig. 1. Experimental set-up.

Fig. 2. Flow through a straight 1m long pipe.

Fig. 3. Comparison of results for flow through a straight 1m long pipe.

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Fig. 5. Passage of 60 % ice slurry through an orifice at a flow velocity of 0.4 m/s.